Chapter 27

Magnetic Field and Magnetic Forces

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Goals for Chapter 27

- To study magnetic forces
- To consider magnetic field and flux
- To explore motion in a magnetic field
- To calculate the magnetic force on a semiconductor
- To consider magnetic torque
How to achieve these goals:

This PowerPoint

Read the Chapter

Homework:

9, 13, 17, 37, 39, 43, 45, 47
Introduction

Magnets exert forces on each other just like charges. In fact, you can draw magnetic field lines just like you drew electric field lines.

The bottom line that we will soon discover is that electrostatics, electrodynamics, and magnetism are deeply interwoven.

In the image at right, you see an MRI scan of a human foot. The magnetic field interacts with molecules in the body to orient spin before radiofrequencies are used to make the spectroscopic map. The different shades are a result of the range of responses from different types of tissue in the body.
Magnetism

• Magnetic north and south poles’ behavior is not unlike electric charges. For magnets, like poles repel and opposite poles attract.
Magnetism and certain metals

- A permanent magnet will attract a metal like iron with either the north or south pole.
The geomagnetic north pole is actually a magnetic south (S) pole—it attracts the N pole of a compass.

Magnetic field lines show the direction a compass would point at a given location.

The earth’s magnetic field has a shape similar to that produced by a simple bar magnet (although actually it is caused by electric currents in the core).

The earth’s magnetic axis is offset from its geographic axis.

North geographic pole (earth’s rotation axis)

South geographic pole

The geomagnetic south pole is actually a magnetic north (N) pole.
Magnetic pole(s)?

We observed monopoles in electricity. A (+) or (−) alone was stable and field lines could be drawn around it.

Magnets cannot exist as monopoles. If you break a bar magnet between N and S poles, you get two smaller magnets, each with its own N and S pole.

In contrast to electric charges, magnetic poles always come in pairs and can't be isolated.

Breaking a magnet in two ...

... yields two magnets, not two isolated poles.
Electric current and magnets

In 1820, Hans Oersted ran a series of experiments with conducting wires run near a sensitive compass. The result was dramatic. The orientation of the wire and the direction of the flow both moved the compass needle.

There had to be something magnetic about current flow.
27.2 Magnetic Field

Let's review how we represented electric interactions:

1. A distribution of electric charge at rest creates an electric field \( E \) in the surrounding space.

2. The electric field exerts a force \( F = qE \) on any other charge \( q \) that is present in the field.

We can describe magnetic interactions in a similar way:

1. A moving charge or a current creates a magnetic field in the surrounding space (in addition to its electric field).

2. The magnetic field exerts a force \( F \) on any other moving charge or current that is present in the field.

Given the presence of a magnetic field, what force does it exert on a moving charge or a current?
Magnetic Field Facts For Physics

A magnetic field is a vector field, denoted by $\mathbf{B}$, which points from a magnet’s north pole to its south pole (outside the magnet).

The force on a charged particle moving in a magnetic field is proportional to the particle’s charge and velocity as well as the magnetic field strength.

The magnetic force, $\mathbf{F}$, is perpendicular to both the magnetic field and velocity: $\mathbf{F} = |q|v \perp \mathbf{B} = |q|v \mathbf{B} \sin \phi$

Where $q$ is the magnitude of the charge and $\phi$ is the angle measured from the direction of $\mathbf{v}$ to the direction of $\mathbf{B}$, as shown in figure 27.6 on page 1022.

From the figure you can see we need the right hand rule, and we can express the equation of the force as a cross product.
Right-hand rule for the direction of magnetic force on a positive charge moving in a magnetic field:

1. Place the $\vec{v}$ and $\vec{B}$ vectors tail to tail.

2. Imagine turning $\vec{v}$ toward $\vec{B}$ in the $\vec{v}$-$\vec{B}$ plane (through the smaller angle).

3. The force acts along a line perpendicular to the $\vec{v}$-$\vec{B}$ plane. Curl the fingers of your right hand around this line in the same direction you rotated $\vec{v}$. Your thumb now points in the direction the force acts.
If the charge is negative, the direction of the force is **opposite** to that given by the right-hand rule.
This equation is valid for both positive and negative charges. For negative charges the direction of the force is opposite to the direction of your thumb for the right hand rule. (See Figure 27.7)

The units of B must be the same as F/qv; Ns/Cm, or N/Am which we define as a tesla, T. You may also see the gauss (1G = 10^{-4}T).

We can use this equation to find the magnitude of an unknown magnetic field by measuring the force on a moving test charge.

When a charged particle travels though a region of space where both electric and magnetic fields are present, the total force on the particle can be found by:

\[
\vec{F} = q \vec{v} \times \vec{B}
\]
Right-hand rule II

- Two charges of equal magnitude but opposite signs moving in the same direction in the same field will experience force in opposing directions.

\[ \vec{F} = q\vec{v} \times \vec{B} \]
\[ \vec{F} = (-q)\vec{v} \times \vec{B} \]

Positive and negative charges moving in the same direction through a magnetic field experience magnetic forces in opposite directions.
Direction of a magnetic field with your CRT

A TV or a computer screen is a cathode ray tube, an electron gun with computer aiming control. Place it in a magnetic field going “up and down.”

You point the screen toward the ceiling and nothing happens to the picture. The magnetic field is parallel to the electron beam.

You set the screen in a normal viewing position and the image distorts. The magnetic force is opposite to the thumb in the RHR.

(a) If the tube axis is parallel to the $y$-axis, the beam is undeflected, so $\vec{B}$ is in either the $+y$- or the $-y$-direction.

(b) If the tube axis is parallel to the $x$-axis, the beam is deflected in the $-z$-direction, so $\vec{B}$ is in the $+y$-direction.
Magnetic forces

- Follow Problem-Solving Strategy 27.1.
- Refer to Example 27.1.
- Figure 27.9 illustrates the example.
Magnetic interactions are fundamentally interactions between moving charged particles. These interactions are described by the vector magnetic field, denoted by \( \mathbf{B} \). A particle with charge \( q \) moving with velocity \( \mathbf{v} \) in a magnetic field \( \mathbf{B} \) experiences a force \( \mathbf{F} \) that is perpendicular to both \( \mathbf{v} \) and \( \mathbf{B} \). The SI unit of magnetic field is the tesla T (1T = 1N/A·m)

Read 1029 to 1039

On page 1054: 1&9
27.3 Magnetic Field Lines and Magnetic Flux

- Magnetic field lines may be traced from N toward S in analogous fashion to the electric field lines.

- Refer to Figure 27.11.

At each point, the field line is tangent to the magnetic field vector $\vec{B}$. The more densely the field lines are packed, the stronger the field is at that point.

At each point, the field lines point in the same direction a compass would... therefore, magnetic field lines point away from N poles and toward S poles.
Field lines are not lines of force

The lines tracing the magnetic field crossed through the velocity vector of a moving charge will give the direction of force by the RHR.

Magnetic field lines are *not* “lines of force.” The force on a charged particle is not along the direction of a field line.

The direction of the magnetic force depends on the velocity \( \mathbf{v} \), as expressed by the magnetic force law \( \mathbf{F} = q \mathbf{v} \times \mathbf{B} \).
Magnetic Flux and Gauss’ Law for Magnetism

We define the magnetic flux through a surface just as we defined electric flux. We can divide any surface into area elements $dA$. For each element we determine $B_\perp$, which is $B \cos \phi$ from figure 27.13.

$$d\Phi_B = B_\perp dA = B \cos \phi dA = B \cdot dA$$

Or

$$\Phi_B = \int B_\perp dA = \int B \cos \phi dA = \int \vec{B} \cdot \vec{dA}$$

In the special case where the magnetic field is uniform over a plane surface with total area $A$, $B_\perp$ and $\phi$ are the same at all points on the surface:

$$\Phi_B = B_\perp A = BA \cos \phi$$

With unit of weber ($1 \text{Wb} = 1 \text{T} \cdot \text{m}^2$)
Magnetic flux through an area

In Gauss’ Law the total electric flux through a closed surface is proportional to the total electric charge enclosed by the surface. For a point charge flux does not equal zero, but for a dipole it does. Magnetic monopoles do not exist (at least we haven’t found one yet) so the flux through a surface enclosing a magnetic field must be zero. This is analogous to an electric dipole, a surface surrounding an electric dipole has a net flux of zero.

If the element of area $dA$ is at right angles to the field lines, then $B_\perp = B$; calling the area $dA_\perp$, we have $B = \frac{d\Phi_B}{dA_\perp}$

The magnitude of magnetic field is equal to flux per unit area across an area at right angles to the magnetic field. For this reason, magnetic field $B$ is sometimes called magnetic flux density.
CAUTION

Unlike electric field lines that begin and end on electric charges, magnetic field lines never have end points; such a point would indicate the presence of a monopole. You might be tempted to draw magnetic field lines that begin at the north pole of a magnet and end at a south pole. But as Figure 27.11a shows, the field lines of a magnet actually continue through the interior of the magnet. Like all other magnetic field lines, they form closed loops.

Consider Figure 27.14 below as you try Example 27.2.
27.3 Summary and Homework

A magnetic field can be represented graphically by magnetic field lines. At each point a magnetic field line is tangent to the direction of \( B \) at that point. Where field lines are close together the field magnitude is large, and vice versa. Magnetic flux \( \Phi_B \) through an area is defined in an analogous way to electric flux. The SI unit of magnetic flux is the weber, Wb. The net magnetic flux through any closed surface is zero (Gauss’s law for magnetism). As a result, magnetic field lines always close on themselves.

Read 1039 to 1046.

On page 1055: #13
27.4 Motion of charged particles in a magnetic field

When a charged particle moves in an electric field it is acted on by the magnetic force. The figure shows a simple example of this motion.

Motion of a charged particle under the action of a magnetic field alone is always motion with constant speed. Why? What does this look like? We can use this idea to find the radius of motion.

(a) The orbit of a charged particle in a uniform magnetic field

A charge moving at right angles to a uniform $\vec{B}$ field moves in a circle at constant speed because $\vec{F}$ and $\vec{v}$ are always perpendicular to each other.
Particle motion in a magnetic field

The force causing the circular motion is the magnetic force:

\[ F = |q|vB \]

The resultant motion can be described with a centripetal force:

\[ F = \frac{mv^2}{R} \]

Setting these two equal to each other:

\[ |q|vB = \frac{mv^2}{R} \]

Solving for \( R \):

\[ R = \frac{mv}{|q|B} \]

We can also express this in terms of momentum \((p = mv)\).

The angular speed:

\[ \omega = \frac{v}{R} = \frac{(v|q|B)}{mv} = \frac{|q|B}{m} \]
Motion of charged particles in a magnetic field

The number of revolutions per unit time is \( f = \frac{\omega}{2\pi} \). The frequency \( f \) is independent of the radius \( R \) of the path and is called the cyclotron frequency. Cyclotrons are used in particle accelerators. One common type of particle accelerator used in many homes is the magnetron, used in microwave ovens.

This particle’s motion has components both parallel \((v_\parallel)\) and perpendicular \((v_\perp)\) to the magnetic field, so it moves in a helical path.
A magnetic bottle

• If we ever get seriously close to small-lab nuclear fusion, the magnetic bottle will likely be the only way to contain the unimaginable temperatures ~ a million K.

• Figure 27.17 diagrams the magnetic bottle and Figure 27.18 shows the real-world examples … northern lights and southern lights.
• Consider Problem-Solving Strategy 27.2.

• Follow Example 27.3.

• Follow Example 27.4. Figure 27.21 illustrates analogous motion.
27.4 Summary and Homework

The magnetic force is always perpendicular to \( \nu \) a particle moving under the action of a magnetic field alone moves with constant speed. In a uniform field, a particle with initial velocity perpendicular to the field moves in a circle with radius \( R \) that depends on the magnetic field strength \( B \) and the particle mass \( m \) speed \( \nu \) and charge \( q \).

Page 1055:

15, 17, 25
Velocity Selector: Particles of a specific speed can be selected from a beam of particles by utilizing electric and magnetic forces. We can produce a setup like in figure 27.20 where the electric and magnetic fields are arranged such that for a positive charge the net force on the charge (while traveling at a specific velocity) is zero.

The electric and magnetic forces oppose each other so the sum of the forces yeilds: \( qvB = qE \)

Solving for \( v \): \( v = E/B \)

Only particles with this specific speed will pass through without being deflected by the fields. Will this also work for negative charges?
J.J. Thompson was able to characterize the electron

- Thompson’s experiment was an exceptionally clever combination of known electron acceleration and magnetic “steering.”

- Thompson set the electric potential loss (from A to A’) equal to the kinetic energy gained, and found the charge to mass ratio of the electron.
Bainbridge’s mass spectrometer

- Using the same concept as Thompson, Bainbridge was able to construct a device that would only allow one mass in flight to reach the detector. The fields could be “ramped” through an experiment containing standards (most high vacuum work always has a peak at 18 amu).

- Follow Example 27.5.

- Follow Example 27.6.
The magnetic force on a current-carrying conductor

The force on a particle of charge $q$ was found by the cross product of $qv$ and $B$. From the definition of current density we can apply the same cross product and find the force on a current carrying conductor: (see page 1036 for the derivation)

$$\vec{F} = Il \times \vec{B}$$

for an infinitesimal line segment:

$$d\vec{F} = Idl \times \vec{B}$$

| Image as Pearson Addison-Wesley |
Loudspeaker engineering

- To create music, we need longitudinal pulses in the air. The speaker cone is a very clever combination of induced and permanent magnetism arranged to move the cone to create compressions in the air. Figure 27.28 illustrates this below.
Magnetic force on a straight then curved conductor

• Refer to Example 27.7, illustrated by Figure 27.27.

• Refer to Example 27.8, illustrated by Figure 27.29.
27.6 Summary and Homework

A straight segment of a conductor carrying current $I$ in a uniform magnetic field $B$ experiences a force $F$ that is perpendicular to both $B$ and the vector $l$ which points in the direction of the current and has magnitude equal to the length of the segment. A similar relationship gives the force $dF$ on an infinitesimal current-carrying segment $dl$.

On page 1056: 33, 37, 39.
27.7 Force and Torque on a Current Loop

Since most current carrying conductors form closed loops, it is a good idea to find the total magnetic force and torque on a conductor. Let’s look at a rectangular current loop in a uniform magnetic field, like in figure 27.29.

The loop has lengths $a$ and $b$, the area vector $A$ makes an angle of $\phi$ to the direction of the magnetic field, and the loop carries a current $I$ moving in the diagram as represented.

We can find the force on each side of the loop from the RHR. The force on the side of length $a$ is $F = IaB$. The force on side of length $b$ is $F' = IbB \sin(90^\circ - \phi) = IbB \cos \phi$.

The forces on either side of the loop cancel out: The net force on a current loop in a uniform magnetic field is zero. However, the net torque is not in general equal to zero.
27.7 Force and Torque on a Current Loop

Remember: Torque is the force times lever arm times the sine of the angle between them.

$F'$ and $-F'$ act along the same line and give rise to zero net torque. Only $F$ and $-F$ give rise to a net torque. The torque by these two forces add to give:

$$\tau = 2F(b/2) \sin \phi = IBa (b \sin \phi) = IBA \sin \phi$$

$IA$ is also called the magnetic dipole moment or magnetic moment, $\mu$: $\tau = \mu B \sin \phi$

We can define a vector magnetic moment with magnitude $IA$. Use the RHR.

We can express this interaction in terms of the torque vector which we used for electric dipole interactions.
More equations:

Torque can be expressed as the cross product of the magnetic moment and magnetic field.

\[ \vec{\tau} = \vec{\mu} \times \vec{B} \]

This is analogous to the torque exerted by an electric field on an electric dipole with dipole moment \( p \).

Like the electric field: When a magnetic dipole changes orientation, the magnetic field does work on the dipole, with a corresponding change in potential energy.

\[ U = -\vec{\mu} \cdot \vec{B} = -\mu B \cos \phi \]

\( U \) is zero when the moment is perpendicular to the magnetic field.

Be sure to read about the solenoid on page 1042 and additional sections on magnetic dipoles on pages 1044 and 1045.
Force and torque on a current loop

Keep in mind figure 27.29 as you try Examples 27.9 through 27.11.

(a) The two pairs of forces acting on the loop cancel, so no net force acts on the loop.

However, the forces on the a sides of the loop ($\vec{F}$ and $-\vec{F}$) produce a torque $\tau = (IBa)(b \sin \phi)$ on the loop.

$\phi$ is the angle between a vector normal to the loop and the magnetic field.

(b) The torque is maximal when $\phi = 90^\circ$ (so $\vec{B}$ is in the plane of the loop).

(c) The torque is zero when $\phi = 0^\circ$ (as shown here) or $\phi = 180^\circ$. In both cases, $\vec{B}$ is perpendicular to the plane of the loop.

The loop is in stable equilibrium when $\phi = 0^\circ$; it is in unstable equilibrium when $\phi = 180^\circ$. 
27.7 Summary and Homework

A current loop with area $A$ and current $I$ in a uniform magnetic field $B$ experiences no net magnetic force, but does experience a magnetic torque of magnitude $\tau$. The vector torque $\tau$ can be expressed in terms of the magnetic moment $\mu$ of the loop, as can the potential energy $U$ of a magnetic moment in a magnetic field $B$. The magnetic moment of a loop depends only on the current and the area; it is independent of the shape of the loop.

On page 1057: 43, 45, 47